Island-trapped waves, internal waves, and island circulation

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LONG-TERM GOALS

To understand oceanic flow around islands and to better predict them using basin-scale observations.

OBJECTIVES

To obtain spatial surveys of currents and hydrography around a large and small (with respect to the Rossby radius) islands in the North Equatorial Current (NEC) and in the North Equatorial Countercurrent (NECC).

When the extent of the topography is larger or smaller than the deformation radius, the topographic effects on circulation are different. Going from large to small scales, several relevant processes are noted below.

- Basin-scale wind and/or wind stress curl drives NEC and western boundary currents (WBC) at large islands (Godfrey, 1989; Firing et al., 1999);
- Westward propagating eddies and/or Rossby waves encounter large islands and produce boundary currents (Firing and Merrifield, 2004);
- Local wind forcing can produce island trapped waves (Merrifield et al., 2002)or near-inertial internal waves (NIW) with amplified displacements at topography (Colin, Rudnick, and Terrill, pers. comm.)
- Steady, strong flow (i.e., NEC or NECC) over a submarine ridge produces arrested lee waves, which exert drag on the current (Klymak et al., 2010), generate turbulence in their lee (Eakin et al., 2011), and may be an energy sink for the geostrophic circulation (Wright et al., 2014);
- Strong flow at small islands leads to persistent submesoscale features: e.g., upwelling on the upstream side, flow constriction over the flanks, downwelling on the downstream side, turbulence in the island wake, and downstream eddies (Gove et al., 2006; Chang et al., 2013).

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APPROACH

Some of the processes itemized above were investigated with quasi-synoptic surveys to:

- Assess the incident mean/eddy flow and the WBC at a large island in relation to local or remote forcing (Figures 1–4);
- Measure persistent submesoscale features (i.e., island-driven upwelling, turbulent wakes, and locally-generated eddies) around small islands (Figures 5–6); and
- Observe lee wave generation where a strong current impinges on a tall, steep submarine ridge (Figures 7–9).

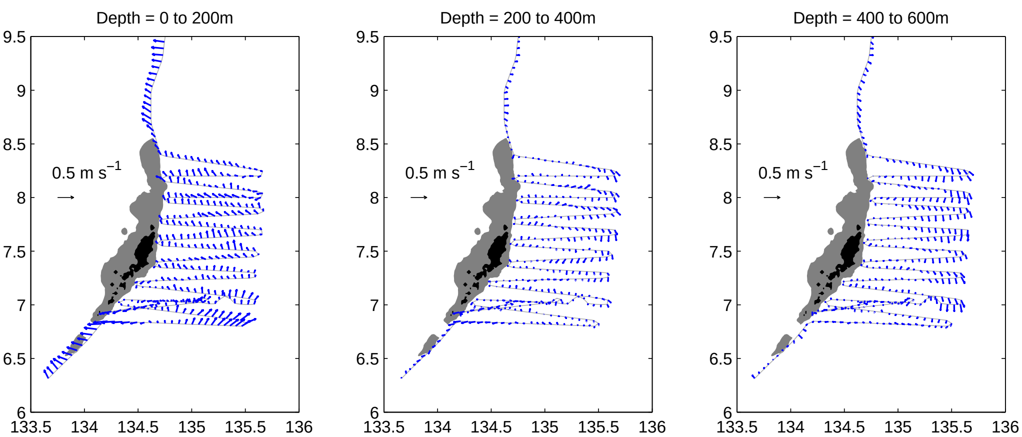

Figure 1: **Left:** ***During survey 1, currents in the upper 200 m were mainly northward along the east coast of Palau roughly consistent with geostrophic estimates from AVISO SSH. Flow below Peliliu was westward. Between these flows, a possible stagnation point near the southeast coast is seen.*** **Middle and right:** ***Southward flow is found offshore with weaker flows inshore.***

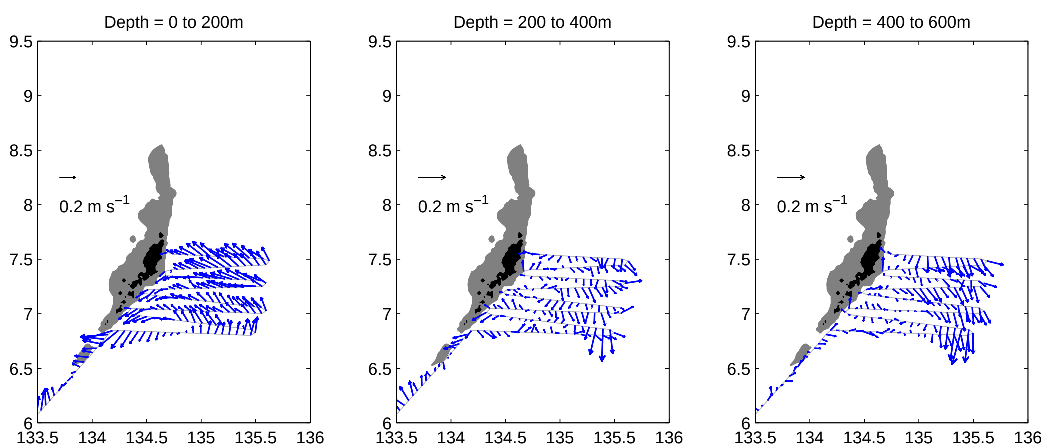

Figure 2: **Left:** ***During survey 2, a southward boundary current in the upper 200 m was found. Flow below Peliliu was westward. Currents were northward further offshore.*** **Middle and right:** ***At depth, maximum southward flow is found offshore.***

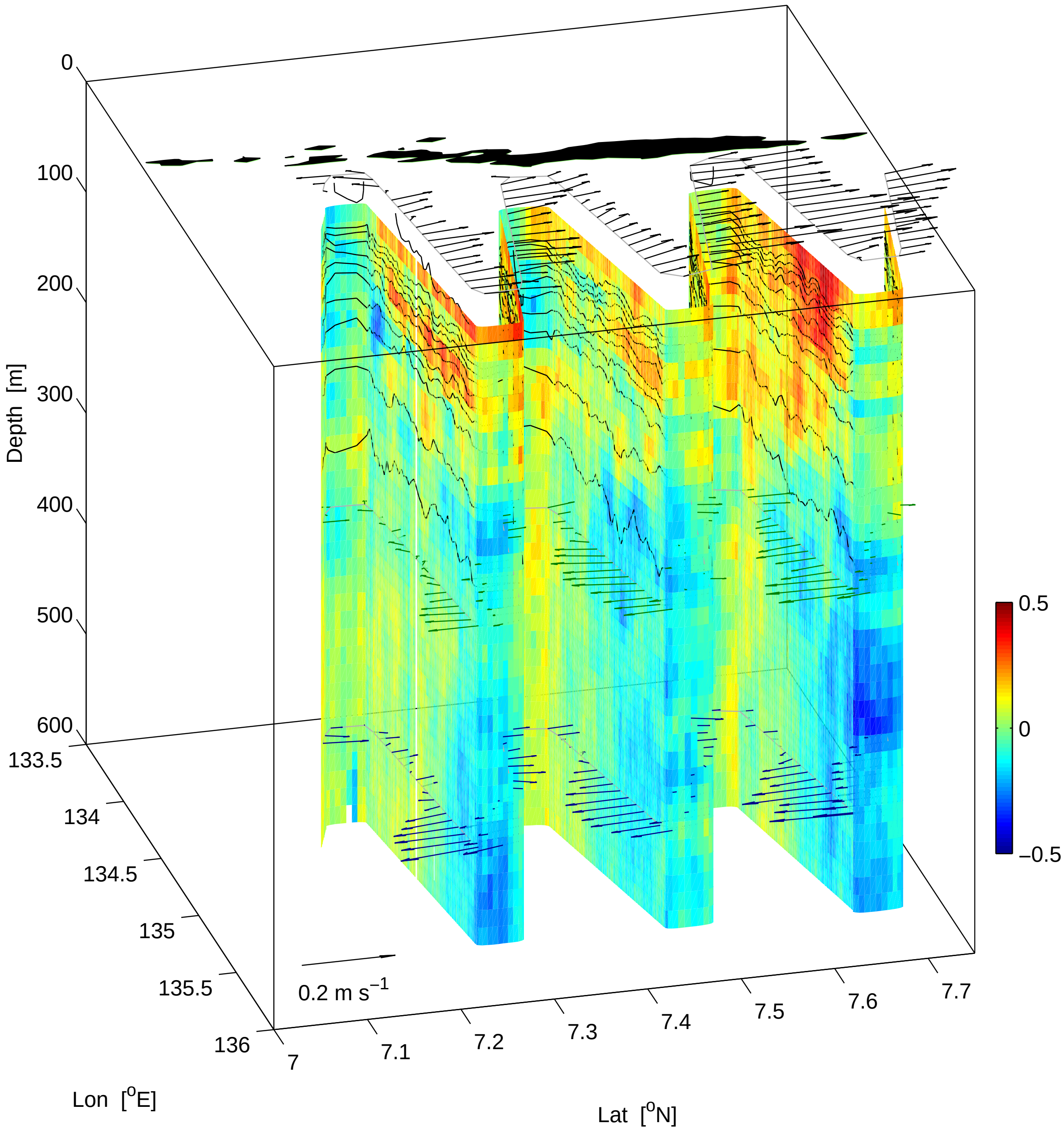

Figure 3: Some depth/cross-shore sections of v in m s^{-1} from survey 1 are shown with northward flow in the upper 200 m and southward flow below 200 m in the offshore area. Current vectors are means from 28–200 m, 200–400 m, and 400–600 m. Black lines are isopycnals at 0.5 kg m^{-3} intervals. The topography of the main islands of Palau are shaded black.

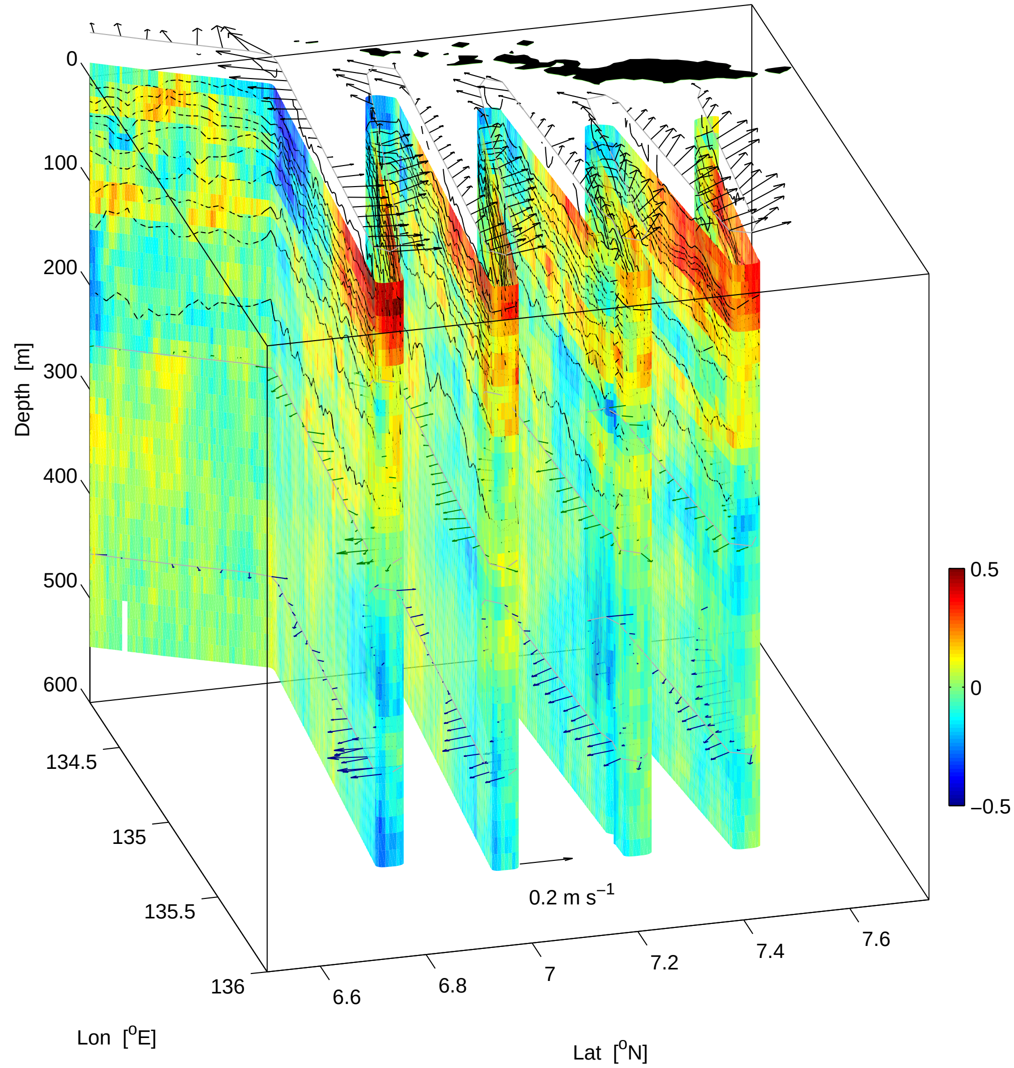

Figure 4: Some depth/cross-shore sections of v in m s^{-1} from survey 2 are shown with a southward boundary current in the upper 200 m and northward/northwestward flow in the offshore area. Currents are southward further offshore and deeper. Current vectors are means from 28–200 m, 200–400 m, and 400–600 m. Black lines are isopycnals at 0.5 kg m^{-3} intervals. The topography of the main islands of Palau are shaded black.

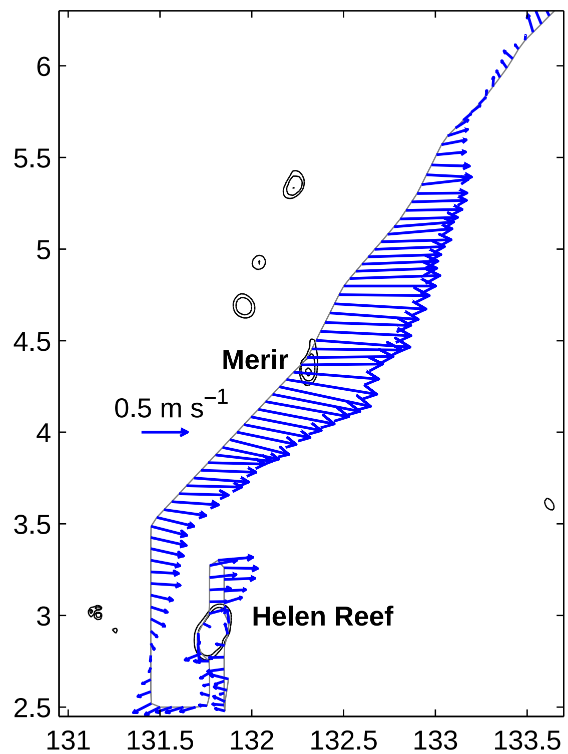

Figure 5: The NECC's depth-mean eastward currents from 28–200 m are maximum near Merir Island. The NECC extends from 3–5.5°N. Black lines are isobaths at 0, 500, and 1000 m.

These surveys were made with SeaSoar, which was towed from R/V *Revelle* on a cruise in March–April 2014. Currents (denoted u and v, which are positive east- and northward), potential temperature (θ), and salinity (S) were obtained from *Revelle*'s Doppler sonars and SeaSoar, an undulating vehicle equipped with a conductivity-temperature-depth (CTD) instrument. SeaSoar completes a dive cycle from 5–400 m every $\sim$10 minutes or $\sim$3 km while being towed at 8 knots. Shipboard Doppler sonars included the Hydrographic Doppler Sonar System (HDSS) with 50 and 140 kHz systems for profiling to $\sim$700 and 300 m as well as an RDI Ocean Surveyor (OS) 75 kHz acoustic Doppler current profiler (ADCP) and a narrowband 150 kHz ADCP. The OS75 was operated in narrowband mode only to provide better statistics over its maximum depth range.

Substantial differences in the boundary currents near the main islands of Palau and NECC flow by Helen Reef and Merir Island were noted between the 2013 and 2014 cruises and even between repeated surveys on each cruise. While some similarities are noted with geostrophic flow from altimetric SSH anomalies on both cruises, there are also considerable differences- such as general northward flow switching to a southward boundary current in the upper 200 m on the south east coast of Palau (Figures 1–2). Combining these data with basin-scale data (i.e., Argo and altimetry) in state estimates by Bruce Cornuelle (SIO) is a necessary step to assess basin-scale forcing of the WBC and the role of eddies/Rossby waves. Measurements from the 2013 and 2014 cruises complement sustained observations from a coastal instrument array (Eric Terrill, SIO) and glider lines around Palau (Dan Rudnick, SIO) which can provide descriptions of temporal variability.

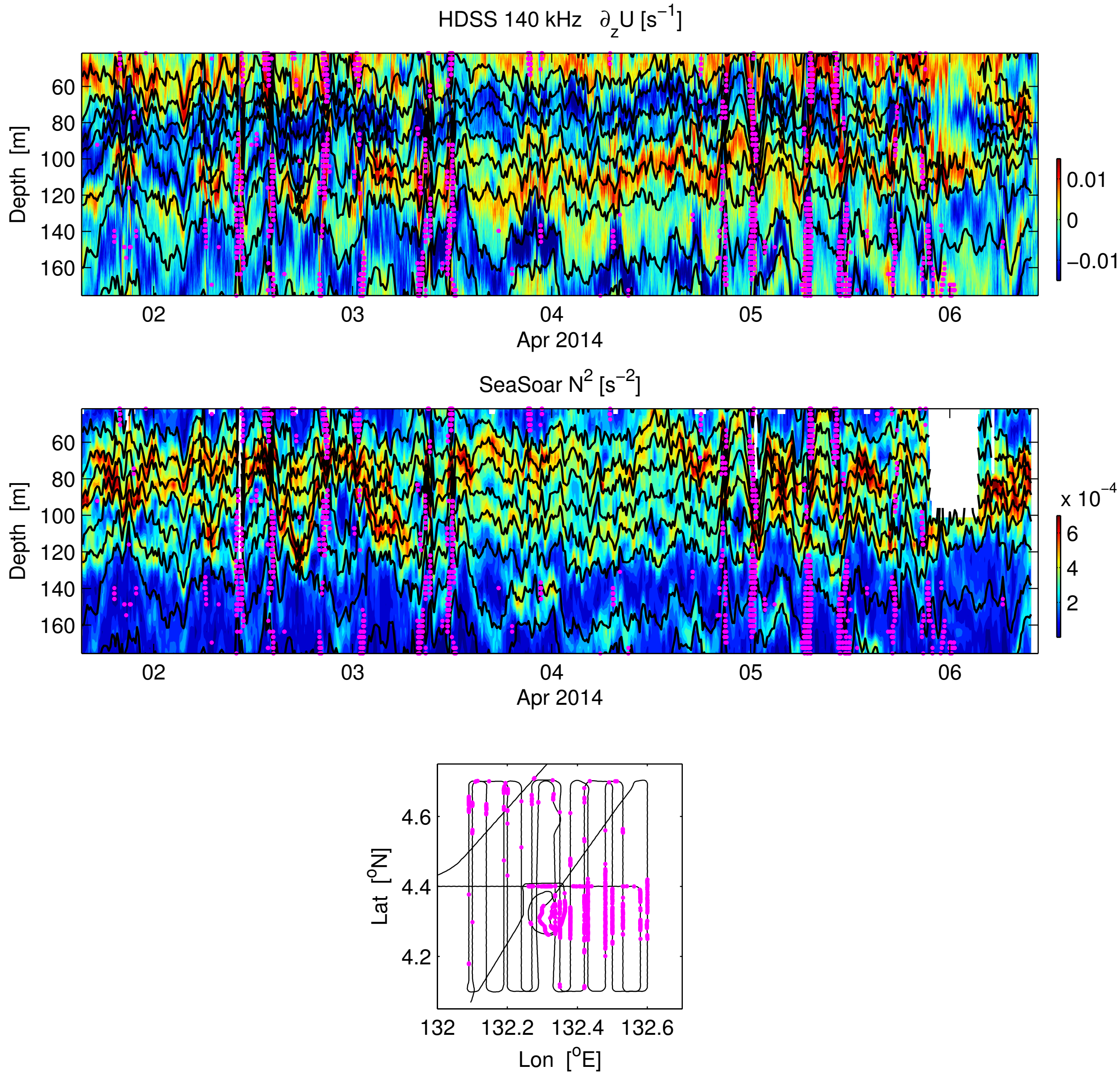

Figure 6: **Bottom:** ***During the surveys around Merir Island, regions where reduced shear is positive may develop shear instability (magenta dots). The island/ridge wake and the northern survey area show concentrations of positive reduced shear. Merir Island is at 4.3°N, 132.3°E.*** **Middle:** ***Buoyancy frequency squared in colour with isopycnals.*** **Top:** ***Eastward shear from the HDSS 140 kHz in colour with isopycnals (black) in 0.5 kg m^{-3} intervals.***

Figure 7: A line of sheared current (indicated by white arrows) is visible, where the NECC is forced over a submarine ridge. Water depth at this time was >500 m, not much less than the ship's distance from the island. Similar straight, north-south lines extending for kilometres were also seen further downstream of the island, which suggest the presence of lee waves.

WORK COMPLETED

SeaSoar cruise

The cruise comprised: a meridional section southward to Palau (8.5–11.5°N), cross-shore sections off the east coast of the main islands of Palau (from 6.5–8.5°N, Figures 1–4), a section across the NECC (4–6.5°N, Figure 5), a short survey around Helen Reef (∼3°N), and two intensive surveys of NECC flow around Merir (4–5°N, Figures 6–9), where currents were strongest. Survey 2 of the main islands was shorter due to tropical storm Peipah, which the ship avoided near Merir. Multibeam bathymetry covered a similar area to the 2013 cruise, but some gaps were filled in and some more coverage was obtained especially near Merir Island. Weather balloon deployments were made by personel from NAVMAR.

Outreach

During the cruise, while surveying around Helen Reef, *Revelle* received a radio call from the conservation officers on the island asking for assistance due to a delayed resupply mission to this outlying island. Since the ship had not yet cleared into the country, we obtained an exception from the government of Palau to allow us to deliver some water and food to the officers. Governor Patris of Hatohobei State and the Coral Reef Research Foundation were helpful in obtaining the necessary permissions.

After the cruise, tours of *Revelle* were given to high school students, Palauan officials, and US embassy personnel. Areas covered included: the scientific instruments and results, the ship itself (i.e., the bridge, engine room, labs, cabins, and mess), and a video about work at sea.

Capt. Murline and the crew of *Revelle* were extremely helpful in these activities.

Graduate education

Celia Ou, a graduate student starting her second year, has been recruited for this project. She has made solid progress in the past few months on preparing the data for scientific analysis. These data will form

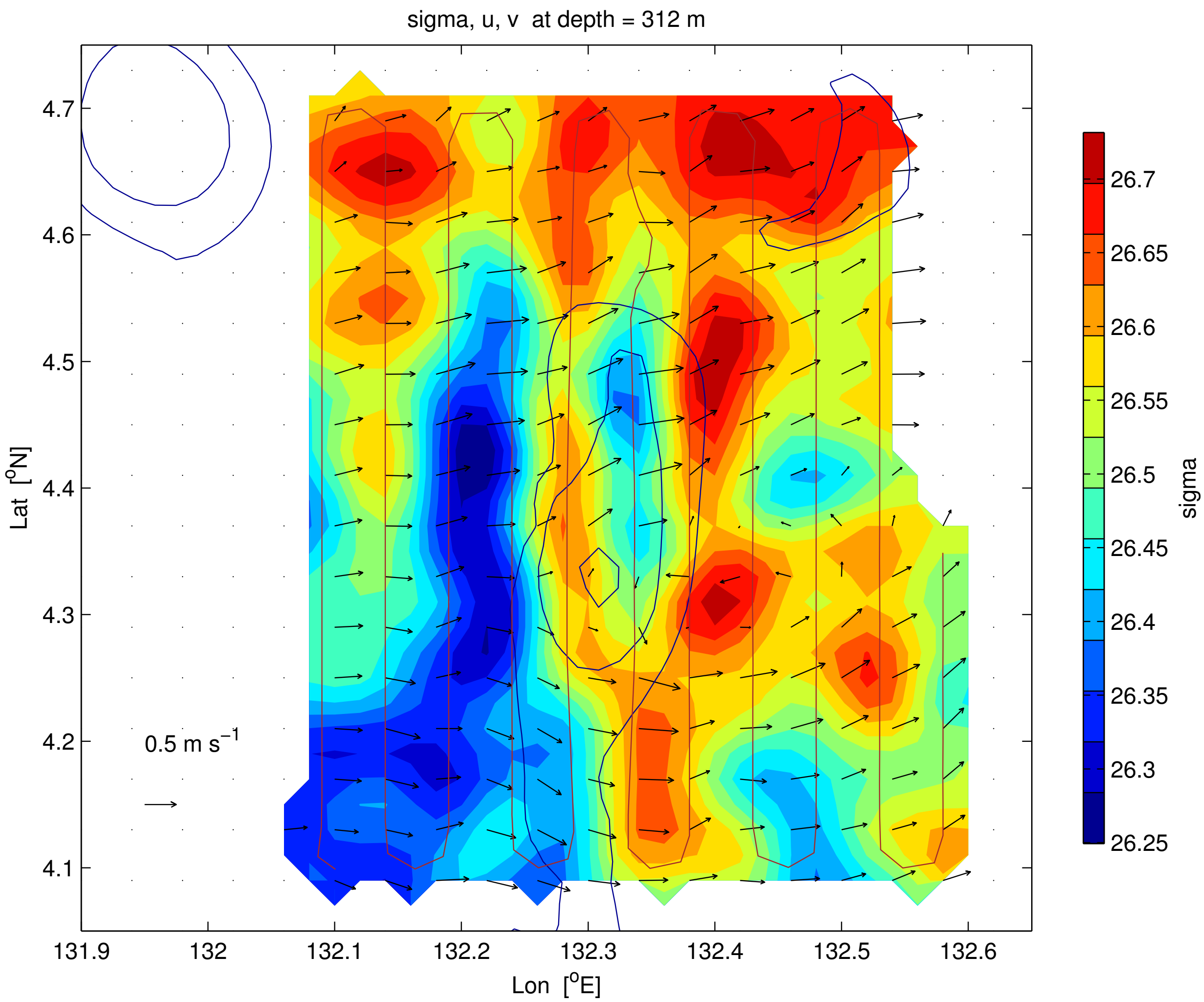

Figure 8: From survey 2 around Merir, an objective map at a depth of 312 m of potential density (σ_θ in kg m^{-3}, coloured shading) and currents (black vectors) shows crests and troughs of lee waves, which are oriented meridionally. The cruise track (brown line) parallels the north-south submarine ridge (bathymetry shown as blue lines: 0, 1000, and 2000 m) in the centre of the survey. Merir Island is at 4.3°N, 132.3°E.

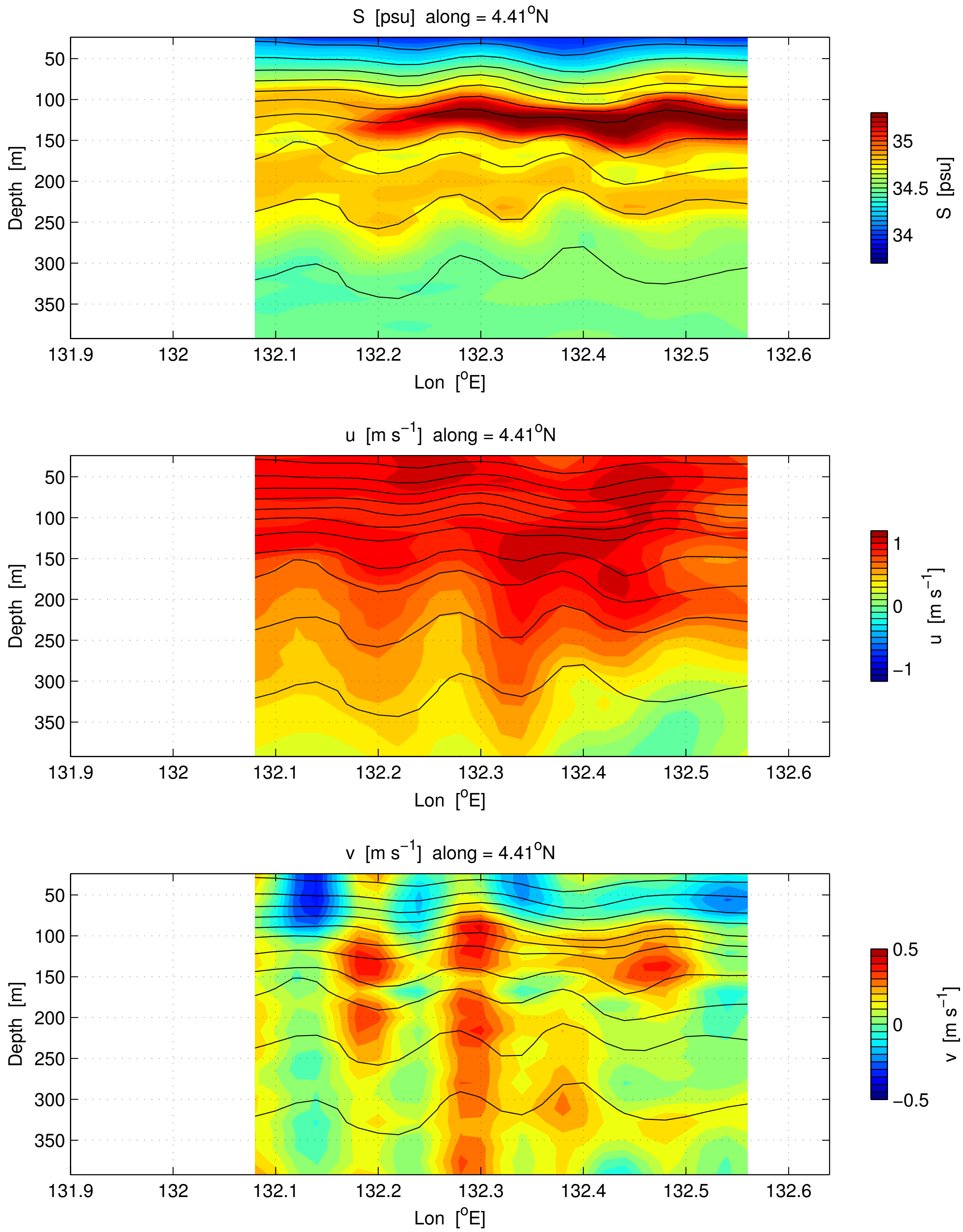

Figure 9: From survey 2 around Merir, a vertical slice along 4.41°N (see Fig. 8) displays upward and westward wave propagation particularly evident in σ_θ (black contours at 0.5 kg m^{-3} intervals). The ridge is near 132.3 °E. **Top:** ***S (coloured shading) displays two subsurface maxima,*** **Middle:** ***u is dominantly eastward with speeds of 1 m s^{-1}.*** **Bottom:** ***v has convergences in the upper 100 m exceed 0.5 m s^{-1} over 10 km or 0.1°, roughly the wavelength of the lee waves.***

the basis of her thesis. Also several graduate students from CICESE (Ensenada, Mexico) and UCSD participated in the cruise to gain at sea experience.

RESULTS

Western boundary current

During survey 1 of the main islands, currents in the upper 200 m were mainly northward along the east coast of Palau (Fig. 1, left) roughly consistent with geostrophic estimates from AVISO sea surface height (figure not shown) but different from the 2013 cruise. Flow south of Peliliu was westward. Between these flows, a possible stagnation point near the southeast coast is seen (Fig. 1, left). Deeper southward flows are found in the offshore area (Fig. 1, right, and Fig. 3).

Survey 2 repeated a portion of survey 1 of the main islands survey towards the end of the cruise. Similarities were noted with the 2013 cruise. During the 2013 cruise, the upstream zonal flow in the offshore area separated near the coast into a stronger ($\sim$0.5 m s^{-1}) southward boundary current and weaker ($\sim$0.3 m s^{-1}) northward boundary current. Similar to the 2013 cruise, a southward boundary currents was present (Figs. 2 and 4). In the offshore area, flow varies from northward to northwestward. Southward flow is found at depth.

Arrested lee waves

On this cruise, the NECC was maximum near 4.5°N, which is about 1° further north than the previous cruise (Fig. 5). (The θ-S properties of the major currents have not yet been examined and compared to nominal characteristics.) A mainly zonal current with a maximum of 1.2 m s^{-1} was incident on Merir Island, similar to the situation on the previous cruise when the NECC was flowing around Helen Reef. Current shear around Merir was visible from the ship in north-south bands of roughened water extending in straight lines for kilometres suggestive of lee waves (Fig. 7).

Two surveys around Merir were done to examine how the flow goes around the island and the submarine ridge. Preliminary objective maps in the horizontal plane were made of the density data from SeaSoar and currents from the OS75 ADCP. Isopycnals show the presence of lee waves with a wavelength of about 0.1° or 10 km (Fig. 8) (Baines, 1995). The waves are present throughout the survey area. A zonal slice through these objective maps also shows upward and upstream phase propagation of the lee waves both in isopycnals and velocities (Fig. 9). Flow convergence near the surface is at least 0.5 m s^{-1} over a wavelength of about 10 km (Fig. 9, middle and bottom). To obtain better horizontal resolution, a zonal tow along 4.4°N across the survey area was made at depths of 100–200 m.

Island wake

Reduced shear is obtained as $S_r^2 = S^2 - 4N^2$, where $S^2 = (\partial_z u)^2 + (\partial_z v)^2$ and N is the buoyancy frequency. Regions of positive reduced shear may be susceptible to shear instability and turbulence. Such regions are found in the north of our survey area where lee wave amplitudes may be larger and in the island/ridge wake (Fig. 6). Similar wake effects have been well studied (Chang et al., 2013, and references therein).

IMPACT/APPLICATIONS

These data will be useful for assessing state estimates of the tropical Pacific produced by Bruce Cornuelle (SIO) using data obtained upstream of the islands in this study.

While internal tides have energy conversion rates of $\mathcal{O}(100\ \mathrm{mW\ m^{-2}})$ in the western Pacific, little energy is lost from the barotropic tide in the vicinity of Palau (Egbert and Ray, 2003). However, geostrophic flow over the abrupt topography may input $\mathcal{O}(0.1\text{–}100\ \mathrm{mW\ m^{-2}})$ into lee waves in a patchy pattern below 10°N in the waters of Palau and the Federated States of Micronesia according to estimates by Nikurashin and Ferrari (2013). The lee wave energy estimates are based on modelled geostrophic flow and Smith-Sandwell bathymetry, which may underestimate the roughness on the scales of rough topography in the western Pacific (Smith and Sandwell, 1997). Further analysis of this cruise's data may help with understanding how relevant lee wave generation and propagation are in this region of rough topography (i.e. tall, isolated seamounts and ridges that extend into the thermocline). Lee wave effects may be quite important locally, but not resolved or visible on a global map.

RELATED PROJECTS

Concurrent with these cruises, (a) state estimates of the tropical Pacific are being made by Cornuelle (SIO), (b) coastal measurement arrays around Palau have been deployed by Terrill (SIO), and (c) gliders are repeating cross-shore sections around Palau (Rudnick, SIO). Results from those studies will be used to assess variability of the currents and complements the spatial surveys done here.

The Repated Observations by Gliders in the Equatorial Region (ROGER) project is sustaining a line across the strong Equatorial Undercurrent (EUC) and sharp Equatorial Front (EF) at 93°W out of the Galapagos with Rudnick (SIO), Owens (WHOI), and Karnauskas (WHOI). With 4 gliders deployed at a time, a complete section is obtained every $\sim$10 days. Analysis of seasonal variations in the position and strength of the EUC and EF are underway.

Large internal waves have been previously reported near Palau (Wolanski et al., 2004) and are a common feature near steep topography (e.g. Johnston et al., 2013, and references therein). The Internal Waves In Straits Experiment is related to this topic and has its own annual report. Also the NSF-funded Tasmanian Tidal Dissipation Experiment (TTIDE) with many IWISE PIs (Pinkel, Alford, Johnston, MacKinnon, Nash, Rainville, Rudnick, and Simmons) is investigating reflection and dissipation of an incident low-mode internal tide impinging on the steep continental slope of Tasmania. Glider results show a relatively narrow (lateral) incident beam. A standing wave pattern is found near the Tasmanian slope with roughly equal incident and reflected wave energies.

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